DEVELOPMENT AND CHARACTERIZATION OF SOLUTION CASTED LAYERED POLYMER COMPOSITES (SCLPC) FOR RADIATION SHIELDING APPLICATIONS

A SYNOPSIS

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1. INTRODUCTION

Composite materials, the product of mixing/stacking two or more materials are a promising attraction to researchers in replacing conventional metallic materials. Although the problems of the product lie in its weak matrix constituting polymers that result in weak inter laminar shear strength, the best use of composite is because of its high specific strength, stiffness, fatigue behavior, and density. There is a profound need of composite materials for a wide range of applications and various scientists across the globe are utilizing the available culture of materials ranging from natural fibers to carbon fibers to fabricate composites. These composite materials find their applications in aerospace, automotive, naval and civil industries. Earlier in the previous century, scientists stepped their foot into the research in composite materials and the last century is the pioneering phase of composite materials. Particularly, in microelectronics, replacement of passive electronic components with passive embedded components attracts researchers due to the minimal utilization of size, reduction in cost and flexibility in circuit design. Moreover, in conductive polymer electronics, the need for thin layer of dielectrics with good dielectric constant, less loss factor and good conductivity makes researchers to think towards a positive alternative.

Further, the need for radiation shielding has increased exponentially owing to the application of nuclear energy sources in various industries like power-plants, transportation, medical fields, etc., Ionizing rays emerged from variety of radiation sources affect both biotic and abiotic species around the globe. The magnitude of the detrimental effect of radiation depends upon the factors like type of radiation, time of exposure and incident energy of radiation. However, owing to the profound applications, the utilization of nuclear radiations cannot be forbidden. In general, high-energy ionizing radiation such as gamma, X-ray and neutron radiation penetrates through the projected objects and materials of high density can shield such radiations. Lead (Pb), the predominantly used radiation shielding material possesses certain drawbacks like heaviness and toxicity leading to focus on the suitable alternatives. The previous works by researchers suggest the usage of natural rubber, high-strength polyimides, polystyrene, low-density polyethylene and epoxy as a matrix for radiation shielding composite materials. It is well known of the fact that the polymer matrix

contains itself a very large quantum of hydrogen atoms that suits very well for radiation shielding.

Nowadays, numerous researches suggest Boron Carbide (B_4C) as a promising alternative for shielding neutron radiation owing to its density, high neutron absorption cross-section, excellent hardness and thermal stability. Moreover, boron carbide is a potential candidate for control rods owing to the almost similar atomic number density as that of the pure boron. In addition, usage of pure boron resulted in poor mechanical properties, which makes B_4C a probable alternative. The preparation of low temperature manufacturing route of lightweight irradiation shields is having a potential demand due to low production cost. Currently, the material used for the spent fuel storage container is lead, due to which the weight of the container for storing a very small fuel capsule is extremely large and the space requirement for the same is also very high. In order to overcome the issues of weight and space, there is a potential demand in materialising an alternate material for lead. Even though, the studies are still underway for the complete replacement for lead, an attempt is made in this work to reduce the material consumption by positively employing boron carbide and lead oxide reinforced epoxy composites with varying compositions. Further, the effect of hybridization and stacking of laminates were also studied in this research work and the results were discussed.

2. LITERATURE REVIEW

The search for irradiation shielding materials has been considerably increased nowadays due to the steep increase in the demand of sophisticated equipment those using radiation and radioactive elements. A shielding material is considered effective for shielding gamma radiation only if the same is affluent of hydrogen and expected to be integrated with heavy metallic elements. It is because heavy elements give rise to inelastic scattering which moderates the fast neutrons. On the other hand presence of hydrogen in the polymer material will cool down the intermediate neutrons as an outcome of elastic scattering. It can be also noted that the heavy elements owing to the possession of great masses can absorb the secondary gamma rays and primary gamma rays as well [1]. It is in general there are two phenomenon those induces damage when a shielding material is subjected to nuclear irradiation. One of such phenomena is elastic scattering of neutrons and another being neutron absorption reaction. Recent researches are considering the fabrication and shielding performance of the latter since the fact

that the constituents of a single composite can execute both the function of thermal absorption and moderation needed for efficient neutron shielding [2].

Further, aluminium composites reinforced with B_4C has good modulus good melting point, high hardness, good tribological and impact properties and possess good chemical resistance [3]. Moreover, these materials can absorb effectively the fast neutrons and thermal neutrons from a wide range of neutrons owing to the high neutron absorption cross-section of Boron thereby enabling the material as a neutron absorber for wet storage pools and dry storage casks as well [4]. Additionally, the behaviour of helium should be noted during the irradiation of B_4C material, which results in the development of helium cluster in the form of bubbles along the grain boundaries leading to end up with structural defects. Numerous studies focused on the B_4C content in the shielding material in order to confirm the suitability in the nuclear shielding applications. It was also reported by researchers that increase in B_4C content tends to increase the neutron shielding ability of the material. Moreover, increase in the mass fraction of B_4C was reported as an aid to increase the hardness of the material, however, that deteriorates the toughness of the material and therefore the fraction is restricted utmost to 30% in order to avoid degradation of mechanical properties [5]. Similarly, hexagonal Boron nitrate could be also utilized for shielding from radiation because of its structure similar to that of graphite, a common material for moderators in nuclear reactors [6].

Epoxy falling under the hydrogenous materials was reported to be beneficial owing to its lightweight property, low shrinkage resulting to dimensional stability, good mechanical strength and chemical resistance. Moreover, aromatic ring in the backbone of epoxy polymer made the same durable over gamma and neutron irradiation. Some scientists have reported the enhancement of flame retardant property of polymers through proper addition of some organic additives [7]. Some characteristics properties like elasticity, high ignition temperature enabled Polydimethylsiloxane as a promising matrix material for shielding [8]. Moreover, it is also reported in few studies about the spectacular improvement in the elastic modulus of the polymers with the addition of nanoparticles without trading off the fundamental benefits like low weight, transparency, easy processing and ductility. Contradictorily, the piling up of nanoparticles resulted in polymer matrix with non-uniformity in the dispersion of

nanoparticles. However, there are prominent processing techniques to overcome this such as functionalization, coating and ultrasonic processing. Several researchers had attempted to fabricate metallic composite shielding materials with the aid of hot extrusion, casting and infiltration [9]. Certain studies on ceramic material like SiC reported its suitability for irradiation environment. The major attractions of using SiC for irradiation situation are its stability and low induced activation.

It is made public that attenuation rate is uncovered to be decreased with the increase in addition of B_4C particularly with aluminium matrix composites. On the other hand, the phenomenal increase in B_4C was reported to end with numerous porous sites in the material leading to less relative density of the material as well. Though it was found to have detrimental effects in the ability of the material to be sintered owing its deprived compatibility between the matrix and the reinforcement materials, but the tensile result was established to have a unique growth positively, conversely disclosed to be resulted with embrittlement of the material [10]. However, works have reported for the careful processing techniques for ensuring complete dispersion of B_4C powders which ended up with zero agglomeration and aggregation of powder particles. One such method is ultrasonic sonication, which results in complete mixture of powder particulates in the resin. The stability of the resin was not traded off upon employing Sonication process. It is also confirmed that with increasing thickness of the material with B_4C, initially the shielding effect increased gradually and then begun to detriment with enlarged thickness [11]. It was reported to be attributed by the reduction in the ability of the material to absorb radiation, which ended up with such a negative response. On the other hand, the presence of bubbles, formation of pores and agglomeration affect the shielding performance of the composite conversely. Reports suggest the usage of Ethylene propylene diene monomer (EPDM Rubber) with boron trioxide to shield effectively the neutron particles irradiation [12]. The increase in neutron attenuation coefficient was observed with increase in B_4C content with epoxy matrix subjected to low velocity ultrasonic stirring [13]. On the other hand, results reveal composites filled with B_4C and Al at a specific combination yielded good neutron shielding properties. Nevertheless, similar trend was observed in the case of polypropelene as the shielding material. Upon irradiation, the material was stated the possession of excellent shielding whereas the ductility of the same shown a negative trend in its growth acknowledging the existence of low mechanical resistance when

exposed to irradiation. It was ended with an observation that when a material was exposed to radiation, the young's modulus of the same was improved which directly means the enhancement of the tensile strength of the material. It was also recommended that adding PbO to the polymer matrix shielding material exhibited appreciable attenuation and shielding properties. Moreover, the growth in the shielding properties was reported with incremental trend upon adding other heavy metals as minor additions with PbO [14].

3. RESEARCH GAP

The following were the gaps identified through the conduction of Literature review:

- Even though, B4C reinforcement in metal and polymers were tried by different researchers, focus on radiation shielding and conductivity studies need further attention especially in polymers.
- Literatures are very limited in case of hybrid polymer composites [B_4C-Al, B_4C-PbO, B_4C-Pb] and hence need more attention.
- Solution Casted-Layered polymer composites [SCLPC] approach is needed to be attended which is expected to give very good results.
- The novel polymer composites in gamma irradiation applications need to be studied.

4. OBJECTIVES

- To develop metallic particles (B_4C, Al, PbO, Pb) reinforced epoxy composites through molding and curing route
- To fabricate novel Solution Casted-Layered polymer composites [SCLPC] (single & tri-layered)
- To develop novel In-situ Solution Casted-Layered polymer composites [IS-SCLPC]
- To study the mechanical properties of the prepared composites.
- To find the suitability of the SCLPC for irradiation shielding applications.
- To investigate the effect of SCLPC combinations on dielectric properties.

4.1. Proposed Methodology

The outline of the proposed methodology is as shown in Figure 1. The research work intends to find the mechanical properties, radiation shielding properties and radiation shielding properties of the Solution casted layered polymer composites.

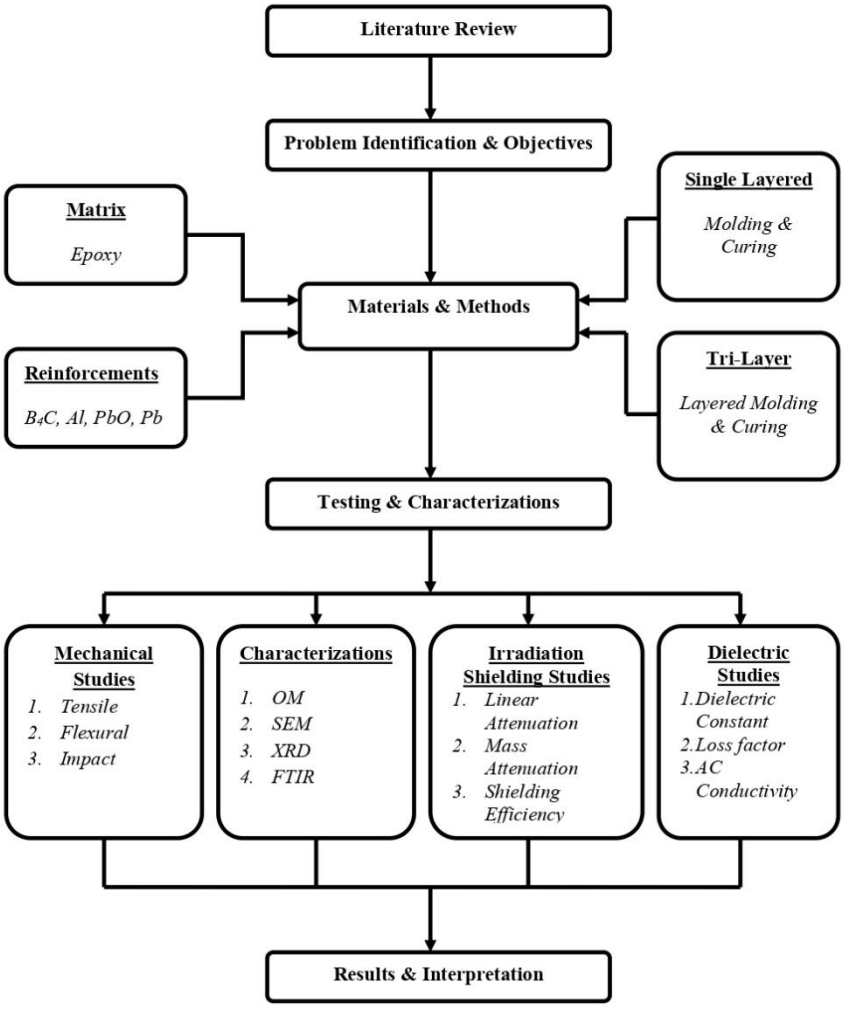

Figure 1: Research Framework.

4.2. Experimental Methodology

4.2.1 Material Development

Epoxy (Grade LY566) and the corresponding hardener (Grade HY951) used for this work were procured from Herenba Resins Pvt. Ltd., Chennai. Commercially available metallic particles boron carbide (B_4C) (99.9%) with particle size 10 μm was purchased from Neena Metal Mart, New Delhi, and the powdered lead (Pb), lead oxide (PbO) and aluminium (Al) particles (99.9%) of particle size 10 μm was purchased from

Alpha Chemika, Mumbai. The confirmation of the powdered particles was done by SEM equipped with an electro dispersive spectrum analyser using JEOL-JSM-5600LV under 20kV and exposure time of 50s.

The composite laminates for radiation shielding were effectively prepared through layered molding and curing route. Rectangular moulds of dimension 300mm × 130mm × 15 mm were used for making the laminates for radiation shielding. Initially the epoxy matrix was taken in the beaker and the B_4C and Pb filler particles were added. The particles were mixed thoroughly for 30 minutes using mechanical stirring in order to eliminate the formation of voids and for ensuring proper dispersion of particles. The procedure is followed by the addition of hardener in the epoxy-hardener weight ratio of 2:1, which is then mixed mechanically for 20 minutes. After thorough mixing, the solution was poured in the glass mould and was allowed to cure for 24 hours. Similarly, layered samples were made in a definite interval of 45 minutes after the pouring of the first and the subsequent layers.

4.2.2 Mechanical *Studies*

The samples prepared were tested for its tensile strength after carefully adhering to the ASTM standard ASTM D638 (165x13x5mm^3). The flexural testing was carried out in accordance to the ASTM standard of dimensions 127x13x5 mm^3 and the impact test was done in accordance with ASTM D256 with specifications 60x13x5 mm^3 using Izod impact tester with a v-notch cut in the samples. The fractograph of the tested samples were done by JEOL-JSM-5600LV scanning electron microscope equipped with EDS. The samples were powdered for studying the thermal degradation.

4.2.3 XRD *& FTIR Analysis*

The powdered sample was subjected to X-Ray diffraction studies using Bruker D8 Advance ECO XRD (Cu Anode) device with scan angle between 20° and 80° for confirming the particle inclusions. Further, the structural stability of the sample after ultrasonication was studied through Fourier Transform Infrared Spectroscopy [Shimudzu IR Tracer 100] at a wavelength up to 4000cm^{-1}.

4.2.4 Radiation *Shielding Studies*

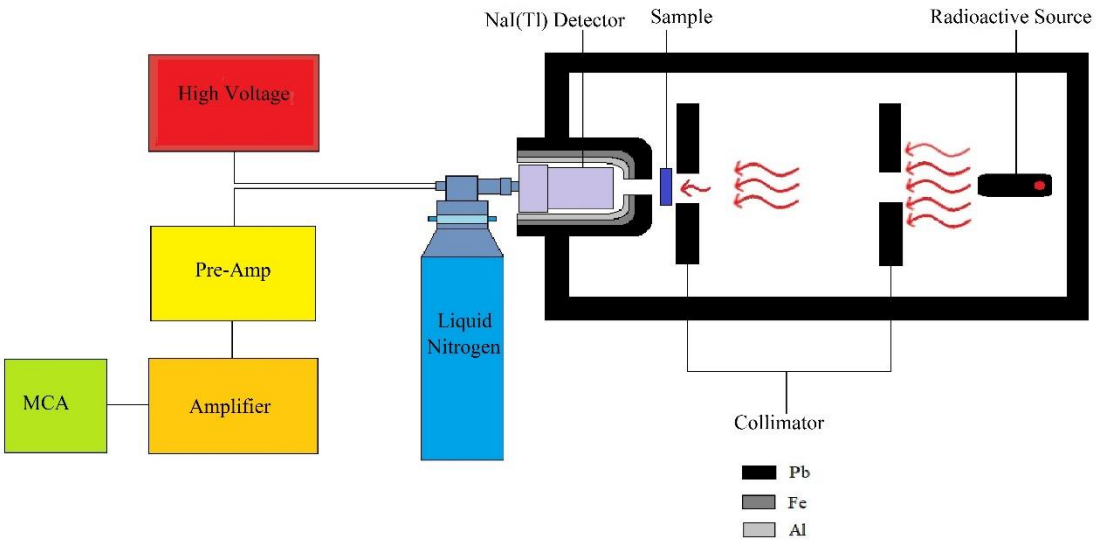

Figure 2: Schematic of the Narrow Beam Geometry Setup

The as prepared samples were studied for its shielding performance using Narrow beam geometry setup as illustrated in Figure 2. For conducting the tests, six different sources of radiation were used for eight different gamma radiation energies. The various sources of radiation are Co^{57} for 122keV, Ba^{133} for 356 keV, Na^{22} for 511 keV and 1275 keV, Cs^{137} for 662keV, Mn^{54} for 840 keV, and Co^{60} for 1170 keV and 1330 keV. The gamma radiations were detected by NaI(Tl) detector. The setup was checked for its reproducibility and stability before and after every set of runs. The signals from the detector are of 8.2% energy resolution at 662keV and are recorded in an EG & GORTEC-13 bit plug in card coupled with a PC/AT. The mass attenuation coefficients of the samples at different energies were measured and the same is used to calculate the parameters like linear attenuation coefficient, half value layer (HVL), tenth value layer (TVL), mean free path (MFP) or the relaxation length and radiation protection efficiency (RPE).

4.2.5 Dielectric Studies

The samples prepared were subjected to electrical characterization to understand the various dielectric behaviors such as, the capacitance C_p and dielectric loss factor tanδ. The studies were conducted at various temperatures ranging from 40˚C

to 150˚C and also with a range of frequencies from 100Hz, 1kHz, 10kHz, 100kHz and 1MHz. LCR Meter Aglient 4284A through parallel plate capacitor method was used for the study. The samples were subjected to annealing in the sample holder at 160˚C prior to observations. The temperature was in a controlled environment with an accuracy of ± 0.5 ˚C and the readings were taken during the cooling process of the sample. The Air capacitance C_a was measured and the dielectric constant of the samples was calculated using the formula $\varepsilon_r = C_p / C_a$. It should be also noted that the AC conductivity of the prepared samples was determined by the following relation

$$\sigma_{AC} = \varepsilon_0 \, \varepsilon_r \, \omega \tan\delta \qquad (1)$$

where ε_0 is the permittivity of free space and ω is the angular frequency and is given by $\omega = 2\pi f$, f is the applied frequency.

5. RESULTS AND DISCUSSION

5.1 Mechanical Studies & Thermal Analysis

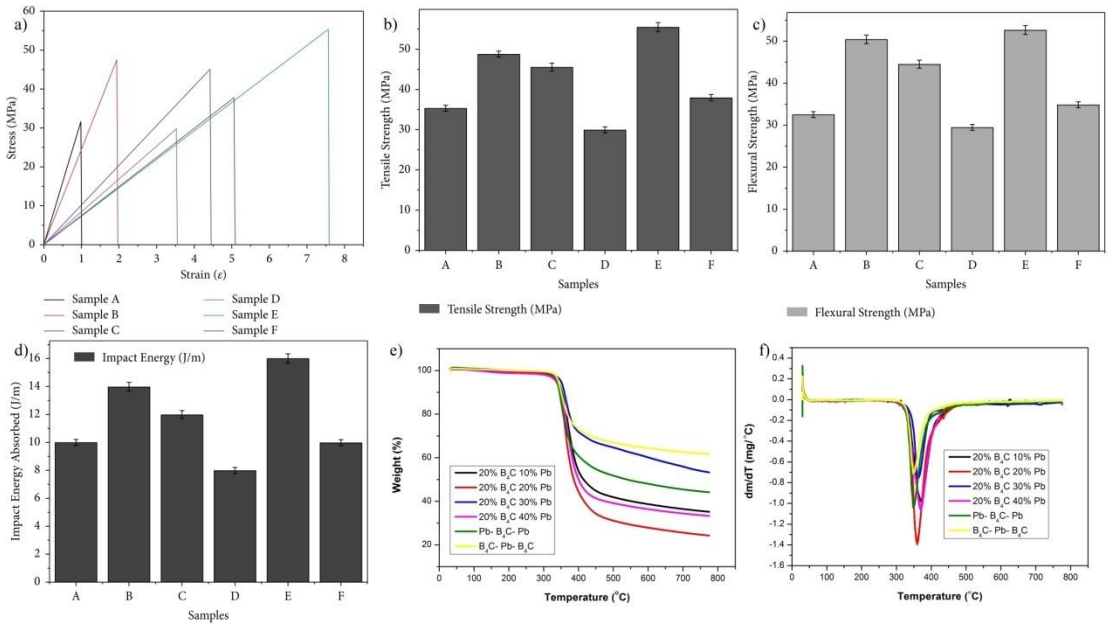

Figure 3: a) Stress-Strain plot of the prepared samples, b) Tensile strength, c) Flexural Strength, d) Impact Energy, e) Primary Thermograph, f) Derivative Thermograph

It is evident from the Figure 3b that the maximum tensile strength of 49.5MPa is obtained for the sample with 20% Pb. It is further evident that as the addition of Pb

content beyond 20% reduces the tensile strength of the sample. It may be attributed by the increase in brittleness of the sample beyond the addition of 20%. Further, it should be noted that some researches revealed the similar scenario of embrittlement upon the addition of B_4C beyond 20%. The sample E layered with 20% Pb as core and with B_4C cladding exhibited good tensile strength. On the other hand, the sample F with Pb cladding was found to have poor tensile strength. Similarly, the elastic modulus of the samples decreased with an increase in the addition of the particles. The reduction in elastic modulus is as evident from the stress- strain diagram depicted in Figure 3a which further shows the similar trend for the tri-layered samples. It is well obvious from the stress-strain curve that the embrittlement of the material took place and the same behaved more like a brittle material.

The Figure 3c above clearly depicts the trend of flexural strength of the various samples. It is obvious from the figure that the single layered sample loaded with 20% of Pb and B_4C exhibited good flexural strength of 50.4 MPa. Further, it is evident that that increase in the composition of lead beyond 30% decreases the flexural strength. On the other hand, the flexural strength of the triple layered sample with B_4C core exhibits lower flexural strength. It is evident from the Figure 3d that the impact performance of the samples yields more at 20% of lead and as the composition of lead increases, the energy absorbed by the specimen decreases and it decreases steeply with 40% addition of lead. The Figure 3e and Figure 3f depicted above clearly elucidates the thermal stability of the as-prepared samples through primary and derivative thermograms. It is evident from the Figure 3e and Figure 3f that single-step degradation is observed in all the samples under Nitrogen environment.

5.2 XRD and FTIR Analysis

The pattern reveals the presence of B_4C, Al, Pb, PbO particles in the matrix. The peaks were in accordance with the JCPDS card 01-078-1665,88-1589, and 85-1739 confirming the occurrence of added particles. Further, the peaks corresponding to the B_4C are at 2θ values at 30.18˚, 37.67˚,52.69˚,55.34˚,64.32˚ and are in accordance with JCPDS card 75-0424. The FTIR corresponds to the ultrasonicated and cured epoxy filled with reinforcements. It can be observed that the broader band at 3428 cm^{-1} corresponds to the stretching of O-H bonds of the hydroxyl groups and is owing to the greater molecular weighted bisphenol A. FTIR further reveals the presence of an

absorption band at 3050 cm^{-1} and is due to the occurrence of oxirane ring. The bands between the wave number 2962 $cm^{-1}$and 2861 cm^{-1} are due to the obvious presence of methylene group. The peaks such as 829 cm^{-1}, 1034 cm^{-1}, 1184 cm^{-1}, 1507 cm^{-1}, 1608 cm^{-1} represents the presence of highly stable aromatic rings and is very obvious from the spectrum.

5.3 Radiation Shielding Studies

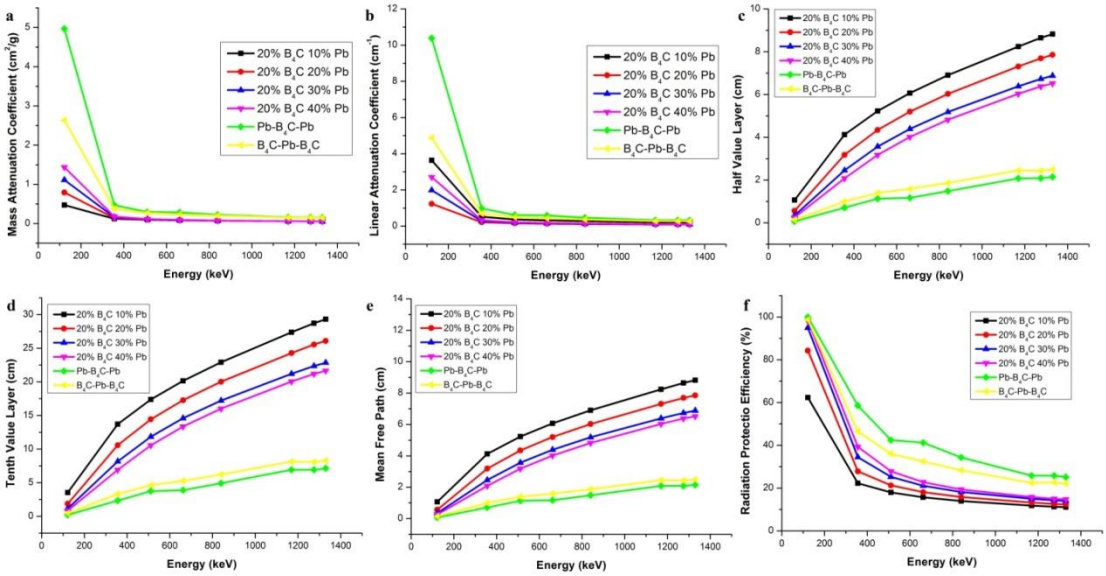

Figure 4: a) Mass Attenuation Coefficient Vs Gamma Radiation Energy, b) Linear Attenuation Coefficient Vs Gamma Radiation Energy, c) Half Value Layer (HVL) Vs Gamma Radiation Energy, d) Tenth Value Layer Vs Gamma Radiation Energy (TVL), e) Mean Free Path (MFP) Vs Gamma Radiation Energy, f) Radiation Protection Efficiency Vs Gamma Radiation Energy

The Figure 4a shows the mass attenuation coefficient (μ_m) of the samples with respect to the incident radiation energy. It is evident from the graph that μ_m for all the samples (both single and tri-layered) decreases with an increase in incident gamma energy. However, the μ_m of the tri-layered sample showed exemplary results at low gamma energies. Particularly, the sample with Pb cladding has a very good mass attenuation coefficient (5 cm^2/g). On the other hand, the sample with B_4C cladding showed a mass attenuation value of 2.85 cm^2/g which is nearly half that of the Pb cladding. The reason for the phenomenon is obvious that the thickness of the sample plays a vital role in accessing the radiation shielding performance. It should be noted that HVL, TVL and MFP are the other predominant parameters, which provides valid

information about penetration of radiation in a material and its shielding capabilities. The above parameters for the as prepared samples are depicted in Figure 4b to Figure 4e and are obvious that these parameters increase with an increase in incident gamma energy. This could be ascribed due to the notion that increase in incident energy leads to the decrease in the chance of interactions between the photons in the material. Moreover, it is well known that the sample with lower HVL, TVL and MFP values results in extraordinary shielding capabilities due to the shorter distance between two interactions of the radiation. From the Figure 4c to Figure 4e the performance of tri-layered samples is obvious owing to the above notions. However, among the single layered samples, the one with 40% Pb (Sample D) shows better shielding properties when compared with the other as-prepared samples. This could be attributed by the increased addition of Pb.

Radiation Protection Efficiency (RPE), is the measure of percentage effectiveness in shielding the incident gamma radiations. The RPE of as prepared samples is illustrated in Figure 4f and it is obvious from the graph that all the samples showcase similar trend in shielding radiation i.e., efficiency decreases with an increase in incident gamma energy. Among the samples, the tri-layered samples with Pb cladding showcases better shielding efficiency of nearly 50% at 662 keV owing to the increased presence of Pb.

5.4 Dielectric Studies

The that dielectric constant increased significantly to a considerable extent with respect to temperature. The segmental mobility of polymer chains could be the possible phenomenon behind the increase in dielectric constant with respect to temperature. It is obvious that the enhancement of orientation of dipole due to segmental mobility leads to the increase in dielectric constant. Moreover, at low frequencies, thermal activation predominates the dipole orientation and segmental mobility, resulting in increased dielectric constant. On the other hand, at higher frequencies, the molecular dipoles could not trace the increment in the frequency owing to lower thermal activation resulting in lower dielectric constant in all the as prepared samples. Nevertheless, increase in particle addition (Pb addition upto 30%) led to increase in dielectric constant of the samples. This is because of the fact that incorporation of conducting fillers in the conductor-insulator composites results in the formation of electrically heterogeneous

material. Similarly, the sample with Pb core has showcased significant improvement in dielectric constant when compared to that of the B_4C core. Further, the improvement in dielectric constant due to particle addition could be attributed due to the increase in interfacial polarization. The samples invariably displayed similar trend in case of the dielectric loss factor (tanδ). The dielectric loss factor founds to increase with an increase in temperature and decrease with an increase in frequency and is owing to the thermal independency at higher frequencies. This is due to the inability of the molecular dipoles to follow the high frequency. The AC conductivity of the samples increases with respect to the increase in temperature and frequency. Here, both the single and tri-layered samples exhibit enhanced AC conductivity when the particle composition is increased. The sample with Pb core displayed better AC conductivity than that of the B_4C core. This could be owing to the fact that in conductor-insulator composites, electron tunneling, a phenomenon in which the electrons will tunnel in between clusters separated by an insulated polymeric layer, is the very obvious reason for the enhancement in AC conductivity.

6. RESEARCH FINDINGS

- The tensile strength, flexural strength and impact energy of the single layered sample with 20% B_4C and 20% Pb exhibited good performance owing to the even particle distribution during the dispersion process.
- However, the mechanical properties were found to decrease with an increase in addition of lead content. This could be because of the softer nature of lead and due to the agglomeration of the particle around the B_4C particles as well as around the matrix.
- The mechanical properties of the tri-layered sample exhibited different trend. The sample with B_4C cladding showcased better performance while comparing to that of the sample with Pb cladding. It was because of the softer core with a harder cladding. Further, the major phenomenon of the failure of the specimen is due to brittle failure.
- The tri-layered sample with B_4C cladding showcased poor mechanical properties which may be because of the hard and brittle nature of B_4C.
- The thermal stability of the single layered sample increased with respect to the addition of B_4C and Pb particles, which may be due to the thermally stable nature

of the particles. Similarly, the tri-layered samples with B_4C cladding portrayed better thermal stability as compared to that of Pb cladding owing to the inert characteristics of B_4C that hinders the mobility of epoxy polymer chain due to thermal effect.

- The radiation shielding study of the samples witnesses the superior characteristics and radiation shielding ability of the Sample D(40% Pb) and Sample E with Pb cladding at incident gamma radiation energy of 662keV.
- At lower energies, all the samples possessed nearly 100% RPE and at 662 keV the sample E possessed nearly 42% which is much higher than that of all the samples. This result in the usage of the as-prepared sample for radiation shielding application of low energy radiation involved in spent fuel caskets and containers.
- The dielectric constant of the samples increased significantly at higher temperatures, which could be due to the segmental mobility of polymer chains.
- On the other hand, at higher frequencies, the molecular dipoles could not trace the increment in the frequency owing to lower thermal activation resulting in lower dielectric constant in all the as prepared samples.
- The dielectric loss factor founds to increase with an increase in temperature and decrease with an increase in frequency and is owing to the thermal independency at higher frequencies.
- The AC conductivity of the samples increased with respect to an increase in temperature and frequency, which could be owing to the phenomenon of tunneling of electrons.

7. ORGANIZATION OF THESIS

- Chapter 1: This chapter illustrate about the basic terms related to composites and its classifications, manufacturing routes, applications and need for polymer composites. It also enunciates the impact of polymer composites in various sectors like mechanical, radiation shielding and electronic sectors.

- Chapter 2: This chapter describes a detailed literature study on the recent research on the polymer composites and layered polymer composites in the field of electronics and radiation shielding. The research gap was identified from the detailed literature survey and the objectives were frame. Based on the objectives the proposed research methodology was developed.

- Chapter 3: This chapter explains about the composition of material elements and process parameters involved in the fabrication of the sample. Also, it explains the radiation shielding studies and dielectric studies involved for the prepared samples. The evaluation methods and ASTM procedure for investigation the tensile test, impact test, and flexural test were also discussed in detail.
- Chapter 4: In this chapter, the influence of particle (B_4C, Al, PbO, Pb) additions on the mechanical properties of epoxy composites was discussed. The fractography mechanism was also discussed with the help of SEM images.
- Chapter 5: In this chapter, the influence of particle (B_4C, Al, PbO, Pb) addition on dielectric properties of hybrid epoxy composites was briefly reported. Further, it briefs about the dielectric constant, loss factor and AC conductivity of the prepared samples.
- Chapter 6: In this chapter, the effect of particle (B_4C, Al, PbO, Pb) addition on radiation shielding properties of epoxy composites was reported.
- Chapter 7: This chapter deals with the effect of hybrid particle reinforcements on the radiation shielding properties Solution Casted Polymer Composites.
- Chapter 8: In this chapter, the effect of tri-layers manufactured through Solution Casted Layered Molding route on the radiation shielding properties was discussed. Moreover, it discusses about the effect of various particle stackings on the radiation shielding properties of the as prepared SCLPCs.
- Chapter 9: In this chapter, the effect of in-situ layer development on the radiation shielding properties of B_4C filled Solution casted layered polymer composites was studied and reported.
- Chapter 10: Based on the results and discussion, the conclusions are made for the research work and the future scopes of the work were discussed in this chapter.

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1. **S. Vignesh,** J. T. Winowlin Jappes, S. Nagaveena, R. Krishna Sharma, and Adam Khan M. Boron Carbide dispersed epoxy composites for gamma radiation shielding applications, *Vacuum*, **205**, (11) (2022) ***I.F- 4.11*** **(SCI**)
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3. **S. Vignesh**, J. T. Winowlin Jappes, S. Nagaveena, R. Krishna Sharma, Adam Khan M, Chaitali V. More, Rajini N and Temel Varol, Development of lightweight polymer laminates for radiation shielding and electronics applications, *International Journal of Polymer Science* (***Accepted-2022***). **I.F-2.973**

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5. **S. Vignesh**, P. Jothiraj, JT Winowlin Jappes, S. Nagaveena, R. Krishna Sharma, Yuvan Nirmal Raja, and Siva Sooriya, Investigation on mechanical behavior of B4C dispersed advanced novel composites fabricated through molding and curing, *Materials Today: Proceedings* **46** (2021): 7639-7642. (**Scopus**)
6. **S. Vignesh**, Winowlin Jappes J T, Nagaveena S, Krishna Sharma R, Adam Khan M, Chaitali V. More, ‘‘Preparation of novel In-situ layered B_4C and PbO reinforced Solution Casted Layered Polymer Composites (SCLPC) for augmenting the gamma irradiation shielding capability”, *Vacuum* (Under Review) ***I.F- 4.11*** **(SCI**)